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Annihilators of Laurent coefficients of the complex power for normal crossing singularity

By

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Abstract

Let f be a real-valued real analytic function defined on an open set of \mathbb{R}^n . Then the complex power f_+^λ is defined as a distribution with a holomorphic parameter λ . We determine the annihilator (in the ring of differential operators) of each coefficient of the principal part of the Laurent expansion of f_+^λ about $\lambda = -1$ in case $f = 0$ has a normal crossing singularity.

§ 1. Introduction

Let \mathcal{D}_X be the sheaf of linear differential operators with holomorphic coefficients on the n -dimensional complex affine space $X = \mathbb{C}^n$. We denote by \mathcal{D}_M the sheaf theoretic restriction of \mathcal{D}_X to the n -dimensional real affine space $M = \mathbb{R}^n$, which is the sheaf of linear differential operators whose coefficients are complex-valued real analytic functions. Let us denote by $\mathcal{D}_0 = (\mathcal{D}_M)_0$, for the sake of brevity, the stalk of \mathcal{D}_M (or of \mathcal{D}_X) at the origin $0 \in M$, which is a (left and right) Noetherian ring.

Let \mathcal{D}'_M be the sheaf on M of the distributions (generalized functions) in the sense of L. Schwartz. In general, for a sheaf \mathcal{F} on M and an open subset U of M , we denote by $\Gamma(U, \mathcal{F}) = \mathcal{F}(U)$ the set of the sections of \mathcal{F} on U . Let $C_0^\infty(U)$ be the set of the complex-valued C^∞ functions defined on U whose support is a compact set contained in U . Then $\Gamma(U, \mathcal{D}'_M)$ consists of the \mathbb{C} -linear maps

$$u : C_0^\infty(U) \ni \varphi \longmapsto \langle u, \varphi \rangle \in \mathbb{C}$$

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which are continuous in the sense that $\lim_{j \rightarrow \infty} \langle u, \varphi_j \rangle = 0$ holds for any sequence $\{\varphi_j\}$ of $C_0^\infty(U)$ if there is a compact set $K \subset U$ such that $\varphi_j = 0$ on $U \setminus K$ and

$$\lim_{j \rightarrow \infty} \sup_{x \in U} |\partial^\alpha \varphi_j(x)| = 0 \quad \text{for any } \alpha \in \mathbb{N}^n,$$

where we use the notation $x = (x_1, \dots, x_n)$, $\mathbb{N} = \{0, 1, 2, \dots\}$ and $\partial^\alpha = \partial_1^{\alpha_1} \cdots \partial_n^{\alpha_n}$ with $\partial_j = \partial/\partial x_j$.

For a distribution u defined on an open set U of M , its annihilator $\text{Ann}_{\mathcal{D}_M} u$ in \mathcal{D}_M is defined to be the sheaf of left ideals of sections P of \mathcal{D}_M which annihilate u . That is, for each open subset V of U , we have by definition

$$\Gamma(V, \text{Ann}_{\mathcal{D}_M} u) = \{P \in \mathcal{D}_M(V) \mid Pu = 0 \text{ on } V\}.$$

Its stalk $\text{Ann}_{\mathcal{D}_0} u$ at $0 \in M$ is a left ideal of \mathcal{D}_0 .

Now let f be a real-valued real analytic function defined on an open set U of M . Then for a complex number λ with non-negative real part ($\text{Re } \lambda \geq 0$), the distribution f_+^λ is defined to be the locally integrable function

$$f_+^\lambda(x) := \begin{cases} f(x)^\lambda = \exp(\lambda \log f(x)) & \text{if } f(x) > 0 \\ 0 & \text{if } f(x) \leq 0 \end{cases}$$

on U and is holomorphic with respect to λ for $\text{Re } \lambda > 0$.

For each $x_0 \in U$, there exist a nonzero polynomial $b_{f,x_0}(s)$ in an indeterminate s and some $P(s) \in (\mathcal{D}_M)_{x_0}[s]$ such that

$$b_{f,x_0}(\lambda) f_+^\lambda = P(\lambda) f_+^{\lambda+1}$$

holds in a neighborhood of x_0 for $\text{Re } \lambda > 0$. It follows that f_+^λ is a distribution-valued meromorphic function on the whole complex plane \mathbb{C} with respect to λ . This is called the complex power, and for a compactly supported C^∞ -function φ on U , the meromorphic function $\langle f_+^\lambda, \varphi \rangle$ in λ is called the local zeta function (see, e.g., [1]).

By virtue of Kashiwara's theorem on the rationality of b -functions ([2]), the poles of f_+^λ are negative rational numbers. Let λ_0 be a pole of f_+^λ and x_0 be a point of U . Then there exist a positive integer m , an open neighborhood V of x_0 , an open neighborhood W of λ_0 in \mathbb{C} , and distributions u_k defined on V such that

$$f_+^\lambda = u_{-m}(\lambda - \lambda_0)^{-m} + \cdots + u_{-1}(\lambda - \lambda_0)^{-1} + u_0 + u_1(\lambda - \lambda_0) + \cdots$$

holds as distribution on V for any $\lambda \in W \setminus \{\lambda_0\}$. To determine the poles of f_+^λ , and its Laurent expansion at each pole is an interesting problem and has been investigated by many authors.

From the viewpoint of D -module theory, it would be interesting if we can compute the annihilator of each Laurent coefficient as above explicitly. For example, we compared the annihilator of the residue of f_+^λ at $\lambda = -1$ with that of local cohomology group supported on $f = 0$ in [3].

In this paper, we treat the case where $f = 0$ has a normal crossing singularity at the origin and determine the annihilators of the coefficients of the negative degree part of the Laurent expansion about $\lambda = -1$. The two dimensional case was treated in [3].

§ 2. Main results

Let $x = (x_1, \dots, x_n)$ be the coordinate of $M = \mathbb{R}^n$.

Proposition 2.1. *The distribution $(x_1 \cdots x_n)_+^\lambda$ has a pole of order n at $\lambda = -1$. Let*

$$(x_1 \cdots x_n)_+^\lambda = \sum_{j=-n}^{\infty} (\lambda + 1)^j u_j$$

be the Laurent expansion of the distribution $(x_1 \cdots x_n)_+^\lambda$ with respect to the holomorphic parameter λ about $\lambda = -1$, with $u_j \in \mathcal{D}'_M(M)$ for $j \geq -n$. Then for $k = 0, 1, \dots, n-1$, the left ideal $\text{Ann}_{\mathcal{D}_0} u_{-n+k}$ of \mathcal{D}_0 is generated by

$$x_{j_1} \cdots x_{j_{k+1}} \quad (1 \leq j_1 < \cdots < j_{k+1} \leq n), \quad x_1 \partial_1 - x_i \partial_i \quad (2 \leq i \leq n).$$

Proof. In one variable t , we have

$$\begin{aligned} t_+^\lambda &= (\lambda + 1)^{-1} \partial_t t_+^{\lambda+1} \\ &= (\lambda + 1)^{-1} \partial_t \left\{ Y(t) + \sum_{j=1}^{\infty} \frac{1}{j!} (\lambda + 1)^j (\log t_+)^j \right\} \\ &= (\lambda + 1)^{-1} \delta(t) + \sum_{j=1}^{\infty} \frac{1}{j!} (\lambda + 1)^{j-1} \partial_t (\log t_+)^j, \end{aligned}$$

where $(\log t_+)^j$ is the distribution defined by the pairing

$$\langle (\log t_+)^j, \varphi \rangle = \int_0^\infty (\log t)^j \varphi(t) dt$$

for $\varphi \in C_0^\infty(\mathbb{R})$.

Let us introduce the following notation:

- For a nonnegative integer j , we set

$$h_j(t) = \begin{cases} \delta(t) & (j = 0), \\ \frac{1}{j!} \partial_t (\log t_+)^j & (j \geq 1) \end{cases}$$

with $\partial_t = \partial/\partial_t$ and

$$h_\alpha(x) = h_{\alpha_1}(x_1) \cdots h_{\alpha_n}(x_n)$$

for a multi-index $\alpha = (\alpha_1, \dots, \alpha_n) \in \mathbb{N}^n$.

- For a multi-index $\alpha = (\alpha_1, \dots, \alpha_n) \in \mathbb{N}^n$, we set

$$|\alpha| = \alpha_1 + \cdots + \alpha_n, \quad [\alpha] = \max\{\alpha_i \mid 1 \leq i \leq n\}.$$

- Set $S(n) = \{\sigma = (\sigma_1, \dots, \sigma_n) \in \{1, -1\}^n \mid \sigma_1 \cdots \sigma_n = 1\}$.

Since

$$(x_1 \cdots x_n)_+^\lambda = \sum_{\sigma \in S(n)} (\sigma_1 x_1)_+^\lambda \cdots (\sigma_n x_n)_+^\lambda,$$

we have

$$u_{-n+k}(x) = \sum_{\sigma \in S(n)} \sum_{|\alpha|=k} h_\alpha(\sigma x).$$

In particular, we have

$$u_{-n}(x) = \sum_{\sigma \in S(n)} \delta(\sigma_1 x_1) \cdots \delta(\sigma_n x_n) = 2^{n-1} \delta(x_1) \cdots \delta(x_n).$$

It follows that $\text{Ann}_{\mathcal{D}_0} u_{-n}$ is generated by x_1, \dots, x_n . This proves the assertion for $k = 0$ since $x_1 \partial_1 - x_i \partial_i = \partial_1 x_1 - \partial_i x_i$ belongs to the left ideal of \mathcal{D}_0 generated by x_1, \dots, x_n .

We shall prove the assertion by induction on k . Assume $k \geq 1$ and $P \in \mathcal{D}_0$ annihilates u_{-n+k} , that is, $P u_{-n+k} = 0$ holds on a neighborhood of $0 \in M$. By division, there exist $Q_1, \dots, Q_r, R \in \mathcal{D}_0$ such that

$$(2.1) \quad \begin{aligned} P &= Q_1 \partial_1 x_1 + \cdots + Q_n \partial_n x_n + R, \\ R &= \sum_{\alpha_1 \beta_1 = \cdots = \alpha_n \beta_n = 0} a_{\alpha, \beta} x^\alpha \partial^\beta \quad (a_{\alpha, \beta} \in \mathbb{C}). \end{aligned}$$

Since

$$(2.2) \quad u_{-n+k}(x) = \sum_{\sigma \in S(n)} \sum_{|\alpha|=k, [\alpha]=1} h_\alpha(\sigma x) + \sum_{\sigma \in S(n)} \sum_{|\alpha|=k, [\alpha] \geq 2} h_\alpha(\sigma x),$$

we have

$$\begin{aligned} u_{-n+k}(x) &= 2^{n-k-1} \delta(x_1) \cdots \delta(x_{n-k}) h_1(x_{n-k+1}) \cdots h_1(x_n) \\ &= 2^{n-k-1} \delta(x_1) \cdots \delta(x_{n-k}) \frac{1}{x_{n-k+1}} \cdots \frac{1}{x_n} \end{aligned}$$

on the domain $x_{n-k+1} > 0, \dots, x_n > 0$. Note that $\partial_i x_i$ annihilates both $\delta(x_i)$ and x_i^{-1} . Hence

$$\begin{aligned} 0 &= Pu_{-n+k} = Ru_{-n+k} \\ &= \sum_{\alpha_1=\dots=\alpha_{n-k}=0, \alpha_{n-k+1}\beta_{n-k+1}=\dots=\alpha_n\beta_n=0} (-1)^{\beta_{n-k+1}+\dots+\beta_n} \beta_{n-k+1}! \dots \beta_n! a_{\alpha,\beta} \\ &\quad \delta^{(\beta_1)}(x_1) \dots \delta^{(\beta_{n-k})}(x_{n-k}) x_{n-k+1}^{\alpha_{n-k+1}-\beta_{n-k+1}-1} \dots x_n^{\alpha_n-\beta_n-1} \end{aligned}$$

holds on $\{x \in M \mid x_{n-k+1} > 0, \dots, x_n > 0\} \cap V$ with an open neighborhood V of the origin. Hence $a_{\alpha,\beta} = 0$ holds if $\alpha_1 = \dots = \alpha_{n-k} = 0$.

In the same way, we conclude that $a_{\alpha,\beta} = 0$ if the components of α are zero except at most k components. This implies that R is contained in the left ideal generated by $x_{j_1} \dots x_{j_{k+1}}$ with $1 \leq j_1 < \dots < j_{k+1} \leq n$.

In the right-hand-side of (2.2), each term contains the product of at least $n - k$ delta functions. Hence $x_{j_1} \dots x_{j_{k+1}}$ with $1 \leq j_1 < \dots < j_{k+1} \leq n$, and consequently R also, annihilates $u_{-n+k}(x)$. Hence we have

$$0 = Pu_{-n+k} = \sum_{i=1}^n Q_i \partial_i x_i u_{-n+k}.$$

On the other hand, since

$$\partial_i x_i (x_1 \dots x_n)_+^\lambda = (x_i \partial_i + 1)(x_1 \dots x_n)_+^\lambda = (\lambda + 1)(x_1 \dots x_n)_+^\lambda,$$

we have

$$\partial_i x_i u_{-k} = u_{-k-1} \quad (k \leq n-1, 1 \leq i \leq n)$$

and consequently

$$0 = \sum_{i=1}^n Q_i \partial_i x_i u_{-n+k} = \sum_{i=1}^n Q_i u_{-n+k-1}.$$

By the induction hypothesis, $\sum_{i=1}^n Q_i$ belongs to the left ideal of \mathcal{D}_0 generated by

$$x_{j_1} \dots x_{j_k} \quad (1 \leq j_1 < \dots < j_k \leq n), \quad x_1 \partial_1 - x_i \partial_i \quad (2 \leq i \leq n).$$

Now rewrite (2.1) in the form

$$P = \sum_{i=1}^n Q_i \partial_1 x_1 + \sum_{i=2}^n Q_i (\partial_i x_i - \partial_1 x_1) + R.$$

If $j_1 > 1$, we have

$$x_{j_1} \dots x_{j_k} \partial_1 x_1 = \partial_1 x_1 x_{j_1} \dots x_{j_k}.$$

If $j_1 = 1$, let l be an integer with $2 \leq l \leq n$ such that $l \neq j_2, \dots, l \neq j_k$. Then we have

$$x_{j_1} \cdots x_{j_k} \partial_1 x_1 = x_{j_2} \cdots x_{j_k} x_1 \partial_1 x_1 = x_{j_2} \cdots x_{j_k} x_1 (\partial_1 x_1 - \partial_l x_l) + \partial_l x_{j_2} \cdots x_{j_k} x_1 x_l.$$

We conclude that P belongs to the left ideal generated by

$$x_{j_1} \cdots x_{j_{k+1}} \quad (1 \leq j_1 < \cdots < j_{k+1} \leq n), \quad x_1 \partial_1 - x_i \partial_i \quad (2 \leq i \leq n).$$

Conversely it is easy to see that these generators annihilate u_{-n+k} since

$$x_1 \partial_1 (x_1 \cdots x_n)_+^\lambda = x_i \partial_i (x_1 \cdots x_n)_+^\lambda = \lambda (x_1 \cdots x_n)_+^\lambda$$

and each term of (2.2) contains the product of at least $n - k$ delta functions. \square

Theorem 2.2. *Let f_1, \dots, f_m be real-valued real analytic functions defined on a neighborhood of the origin of $M = \mathbb{R}^n$ such that $df_1 \wedge \cdots \wedge df_m \neq 0$. Let*

$$(f_1 \cdots f_m)_+^\lambda = \sum_{j=-m}^{\infty} (\lambda + 1)^j u_j$$

be the Laurent expansion about $\lambda = -1$, with each u_j being a distribution defined on a common neighborhood of the origin. Let v_1, \dots, v_n be real analytic vector fields defined on a neighborhood of the origin which are linearly independent and satisfy

$$v_i(f_j) = \begin{cases} 1 & (\text{if } i = j \leq m) \\ 0 & (\text{otherwise}) \end{cases}$$

Then for $k = 0, 1, \dots, m - 1$, the annihilator $\text{Ann}_{\mathcal{D}_0} u_{-m+k}$ is generated by

$$\begin{aligned} & f_{j_1} \cdots f_{j_{k+1}} \quad (1 \leq j_1 < \cdots < j_{k+1} \leq m), \\ & f_1 v_1 - f_i v_i \quad (2 \leq i \leq m), \quad v_j \quad (m + 1 \leq j \leq n). \end{aligned}$$

Proof. By a local coordinate transformation, we may assume that $f_j = x_j$ for $j = 1, \dots, m$, and $v_j = \partial/\partial x_j$ for $j = 1, \dots, n$. Then the distribution u_j does not depend on x_{m+1}, \dots, x_n . Hence we have only to apply Proposition 2.1 in \mathbb{R}^m . \square

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